TITLE: Low-Dimensional Electron Semiconductor Structures as Tunable Far-Infrared Amplifiers and Generators

Ioffe Institute
6th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 22–26, 1998.

Low-dimensional electron semiconductor structures as tunable far-infrared amplifiers and generators

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Abstract. A general analytic theory of voltage tunable solid-state far-infrared (FIR) amplifiers, generators and emitters, based on a current-driven instability of two-dimensional (2D) plasmons in a grating-coupled 2D electron system (ES) is presented.

1 Introduction

An idea of using the radiative decay of grating-coupled 2D plasmons in semiconductor heterostructures in order to create tunable solid-state FIR sourses was being discussed in the literature since 1980. In experimental papers, see e.g. Refs. [1, 2, 3, 4], one uses a semiconductor structure (e.g., GaAs/AlGaAs) with a 2DES at the heterointerface, and a metal grating coupler on top of the sample (Fig. 1, where the incident electromagnetic wave is absent). A strong dc current is passed through the 2DES, and 2D plasmons are excited in the system due to a current driven plasma instability [5]. The grating couples 2D plasmons to an external electromagnetic field, and their energy is converted to FIR radiation with a frequency depending on the dc current. In spite of the strong appeal of this idea and essential improvements of physical parameters of GaAs/AlGaAs samples in recent years, the intensity of the emitted radiation remains to be too weak [4] for device applications.

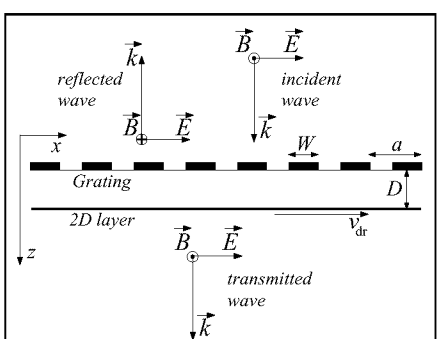

Fig 1. The geometry of the structure.

We present a general electrodynamic theory of a grating-coupled 2DES, both with and without the flowing dc current j_0. We formulate particular recommendations on how to design amplifiers (generators) with desirable characteristics, and show that voltage tunable solid-state FIR amplifiers, generators and emitters can be created in

low-dimensional electron semiconductor heterostructures with experimentally achievable parameters.

2 Formulation of the problem and analytic results

We consider a propagation of electromagnetic waves through the structure shown in Fig. 1 and calculate the transmission $T(\omega, v_{\rm dr})$, reflection $R(\omega, v_{\rm dr})$, absorption $A(\omega, v_{\rm dr})$ and emission $E(\omega, v_{\rm dr})$ coefficients of the structure as functions of the light frequency ω, drift velocity of 2D electrons $v_{\rm dr}$, and other physical and geometrical parameters of the structure (densities, mobilities and effective masses of electrons in the 2DES and in the grating, period of the grating a, width of the grating strips W, distance between the 2DES and the grating D). The period a and the distance D (typically $\simeq 1$ μm or smaller) are assumed to be smaller than the wavelength of light λ (typically > 100 μm). The calculated transmission $t(\omega)$ and reflection $r(\omega)$ amplitudes have the form

$$t(\omega) = r(\omega) + 1 = \frac{1}{\epsilon_{2D}(\mathbf{0}, \omega)} \left(1 - \frac{2\pi f \langle \sigma_{1D}(\omega) \rangle}{c\sqrt{\epsilon_b(\omega)}\zeta(\omega)} \right). \tag{1}$$

The transmission, reflection and absorption coefficients are determined as $T(\omega) = |t(\omega)|^2$, *etc.* In Eq. (1), $f = W/a$, c is the velocity of light, $\epsilon_b(\omega)$ is the dielectric permittivity of the surrounding medium (assumed to be uniform in all the space),

$$\zeta(\omega) = \epsilon_{2D}(\mathbf{0}, \omega) \left(1 + \frac{2\pi i f \langle \sigma_{1D}(\omega) \rangle}{\omega \epsilon_b(\omega)} \sum_{\mathbf{G}} \kappa_G \alpha(\mathbf{G}) W(\mathbf{G}, \omega) \right) \tag{2}$$

is a response function of the structure, the sum is taken over all reciprocal lattice vectors $\mathbf{G} = (2\pi m/a, 0)$, m is integer,

$$W(\mathbf{G}, \omega) = 1 - \left(1 - \frac{1}{\epsilon_{2D}(\mathbf{G}, \omega)} \right) e^{-2\kappa_G D}, \tag{3}$$

$$\epsilon_{2D}(\mathbf{G}, \omega) = 1 + \frac{2\pi i \kappa_G}{\omega \epsilon_b(\omega)} \sigma_{2D}(\mathbf{G}, \omega) \tag{4}$$

and $\sigma_{2D}(\mathbf{G}, \omega)$ are the frequency and wave-vector dependent "dielectric permittivity" and the conductivity of the 2DES, $\kappa_G = \sqrt{G^2 - \omega^2 \epsilon_b(\omega)/c^2}$, $\sigma_{1D}(\omega) \equiv \sigma_{1D}(x, \omega)$ is a (local) conductivity of electrons in the grating [treated as an infinitely thin 2D layer with an electron density $n_1(x)$ at $|x - ma| < W/2$ and a vanishing density at $|x - ma| > W/2$], the angular brackets mean the average over the area of a grating strip, $\langle \ldots \rangle = \int (\ldots) dx/W$, and the form-factor $\alpha(\mathbf{G})$ in Eq. (2) is determined by Fourier components of the normalized equilibrium electron density $\vartheta(x) = n_1(x)/\langle n_1(x) \rangle$ in the grating strips, $\alpha(\mathbf{G}) = |\langle \vartheta(x) e^{i\mathbf{G}\cdot\mathbf{r}} \rangle|^2$.

In Eqs. (1) – (4) electrodynamic effects are taken into account within the classical electrodynamics, nonlocal, quantum-mechanical, and scattering effects in the 2DES, as well as the influence of the flowing current j_0 enter the theory via an appropriate model for the conductivity $\sigma_{2D}(\mathbf{G}, \omega)$, the conductivity $\sigma_{1D}(\omega)$ includes the dependence on the density and the scattering rate (or mobility) of electrons in the grating, a possible frequency dispersion of the surrounding medium is taken into account in function $\epsilon_b(\omega)$.

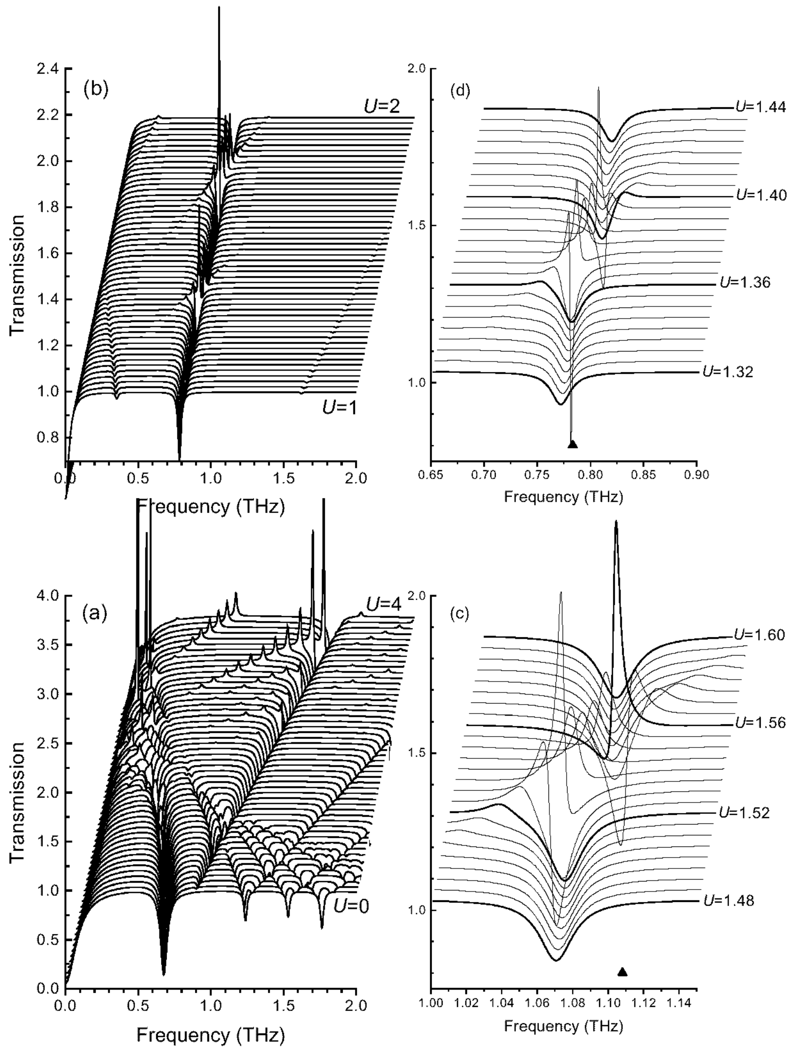

Fig 2. The calculated transmission coefficient $T(\omega, v_{\mathrm{dr}})$ of several structures.

3 Discussion

Figure 2 demonstrates the calculated transmission coefficient of the grating coupled 2DES versus the frequency of light and the dimensionless drift velocity of 2D electrons $U = v_{\mathrm{dr}}/v_{F2}$, at different values of device parameters (v_{F2} is the Fermi velocity). Figure 2a shows $T(\omega, v_{\mathrm{dr}})$ in a large range of drift velocities $0 \le U \le 4$ at parameters taken from Ref. [4] (*metal* grating, $n_2 = 5.4 \times 10^{11}$ cm^{-2}, $\mu_2 = 4 \times 10^5$ cm^2/Vs, $a = 2$ μm, $W = 1.2$ μm, and $D = 62$ nm). One sees a rich excitation spectrum of 2D plasmon modes, but a pronounced amplification of light [$T(\omega, v_{\mathrm{dr}}) > 1$] is achieved only at $U \simeq 3$ which is far beyond realistic experimental possibilities (the estimated maximum drift velocity of 2D electrons in Ref. [4] corresponds to $U \simeq 0.1$).

Using our results we find effective ways to reduce the threshold velocity of amplification down to experimentally achievable values. Fig. 2b demonstrates $T(\omega, v_{dr})$ in a range $1 \leq U \leq 2$ at $n_1 = n_2 = 6 \times 10^{10}$ cm^{-2}, $\mu_1 = \mu_2 = 2 \times 10^5$ cm^2/Vs, $a = 0.175$ μm, $W = 0.1$ μm, and $D = 20$ nm. Physical parameters in this example are taken from Ref. [6], where the drift velocity corresponding to $U \sim 1.8$ has been *experimentally* achieved, geometrical parameters are taken in view of possibilities of modern semiconductor technology (see, e.g., Ref. [7]). Fig. 2b clearly demonstrates that an amplification of FIR radiation is possible at experimentally achievable parameters of modern semiconductor heterostructures. Fig. 2d shows the same $T(\omega, v_{dr})$ dependence on an enlarged scale, Fig. 2c is drawn at a different value of the electron density in the grating strips ($n_1 = 1.2 \times 10^{11}$ cm^{-2}).

The key point which allows us to accomplish the desired aim is the use of a *quantum-wire* grating instead of commonly employed metal ones. The resonant interaction of plasma modes in the 2DES and in the grating leads to a considerable increase of the grating coupler efficiency, and finally to a reduction of the threshold velocity and an enhancement of amplification. Together with other methods [8] (including a specific choice of geometrical parameters of the structure) this allows us to reduce the threshold parameters of the amplifier down to experimentally achievable values. The operating frequency of amplifiers can be varied by the dc electric current flowing in the 2DES and/or by changing the electron density n_1 in the quantum wire grating (compare Figs. 2c and 2d).

4 Conclusion

Voltage tunable solid-state FIR amplifiers, generators and emitters can be realized in low-dimensional electron semiconductor heterostructures with experimentally achievable parameters.

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